Detection of ice and organics on an asteroidal surface

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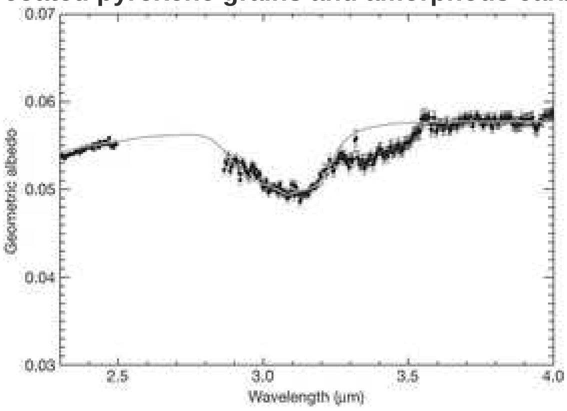
Recent observations, including the discovery[1] in typical asteroidal orbits of objects with cometary characteristics (main-belt comets, or MBCs), have blurred the line between comets and asteroids, although so far neither ice nor organic material has been detected on the surface of an asteroid or directly proven to be an asteroidal constituent. Here we report the spectroscopic detection of water ice and organic material on the asteroid 24 Themis, a detection that has been independently confirmed[2]. 24 Themis belongs to the same dynamical family as three of the five known MBCs, and the presence of ice on 24 Themis is strong evidence that it also is present in the MBCs. We conclude that water ice is more common on asteroids than was previously thought and may be widespread in asteroidal interiors at much smaller heliocentric distances than was previously expected.

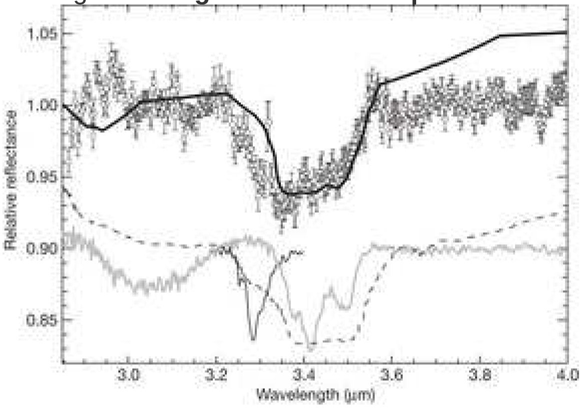
1. Figure 1: **The reflectance spectra of 24 Themis are well fitted by a mixture of ice-coated pyroxene grains and amorphous carbon.**



The spectrum of 24 Themis from 2008 (filled symbols) is plotted (binned ×6) along with an example spectral model that includes a thin coating of water ice on surface grains (grey line). The 24 Themis data are binned to lower spectral resolution and plotted as geometric albedo. The model is an intimate mixture containing 29% pyroxene coated with a 0.045-µm-thick layer of water ice and 71% amorphous carbon[6, 14]. All grains have a diameter of 30 µm. Error bars, 1 sample s.d.

See larger

2. Figure 2: **Organic material is present on the surface of 24 Themis.**



The spectrum of 24 Themis from 2008 has been divided by the model shown in Fig. 1 to identify residual absorptions (open symbols). A residual absorption band centred near 3.4 μm and with a width of ~0.2 μm is well matched by complex organic materials. The thick black line is ice tholin (the residual of an irradiated mixture of water ice and ethane; calculated from optical constants; ref. 9). Offset from the ice tholin and the spectrum/model data by 0.1 units, the dashed line is asphaltite[15], the heavy grey line is the carbonaceous meteorite Cold Bokkeveld (a slope from hydrated silicates has been removed; ref. 11) and the thin black line is an average of six polycyclic aromatic hydrocarbons (ref. 10). Absorption features in organic materials near 3.4 and 3.5 μm are typically $–CH_2$ and $–CH_3$ stretch bands, whereas those near 3.3 μm in the polycyclic aromatic hydrocarbons are aromatic stretch bands. Error bars, 1 sample s.d.

We observed 24 Themis on seven different dates between March 2002 and May 2008 using the SpeX instrument at the NASA Infrared Telescope Facility[3] (IRTF). Observations covered the 2–4-μm wavelength region with a resolution ($\lambda/\Delta\lambda$; λ, wavelength) of 2,500. We used Spextool, a set of Interactive Data Language routines provided by the IRTF, for data reduction[4].

24 Themis was warm enough to contribute a significant amount of thermal flux at the longest wavelengths measured. This flux was removed by application of a modified version of the standard thermal model[5], so that the reflectance spectrum alone could be analysed. All inputs to the standard thermal model are well known for 24 Themis except for the ‘beaming parameter’, η, which can be fitted from the data.

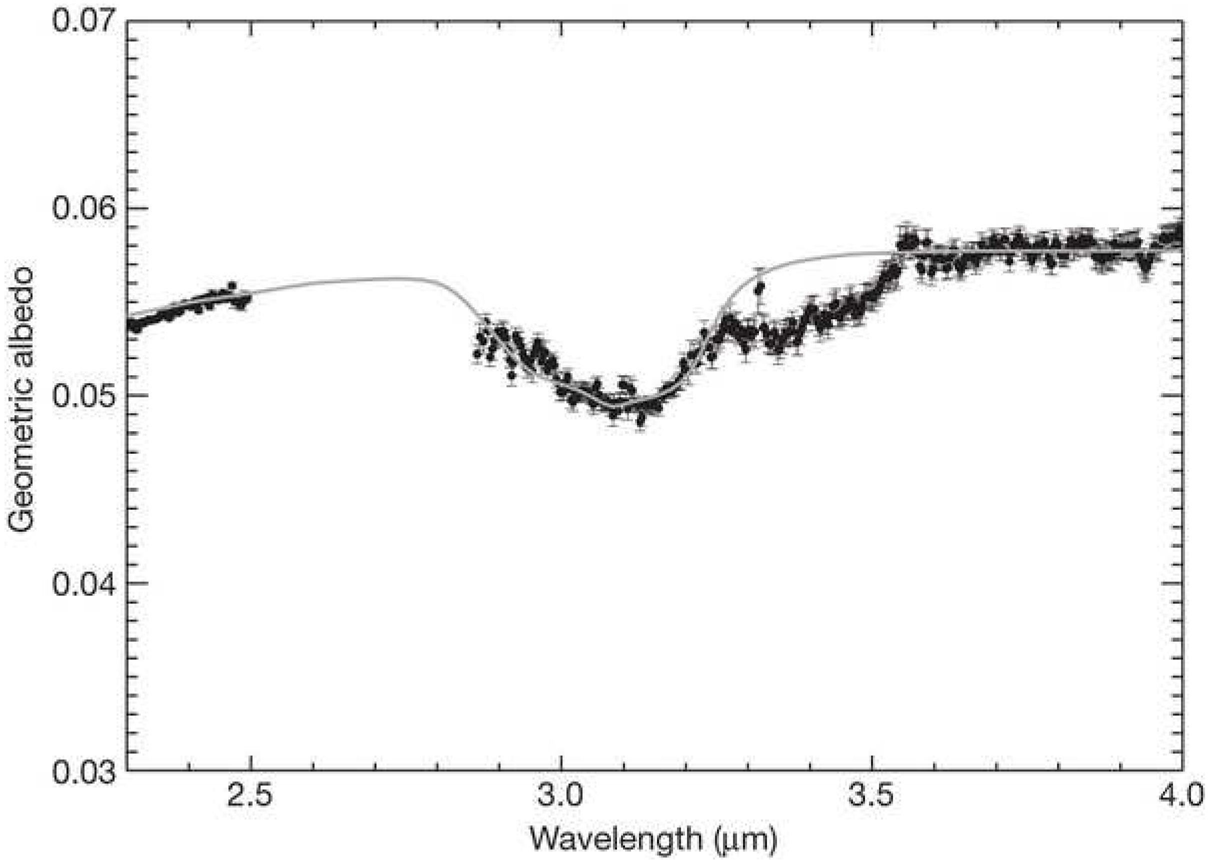
Although these spectra are of varying quality, they are all consistent with one another. The four highest-quality spectra are shown in Supplementary Fig. 1. All spectra show an absorption centred near 3.1 μm and roughly 0.4 μm wide, with a band depth of 10%. The band shape is unlike what is seen in hydrated minerals, carbonaceous chondrites or typical C-type asteroids

(Supplementary Fig. 2). We attribute this band to fine-grained water ice as a frost deposited on regolith grains.

The presence of water ice is qualitatively supported by its widespread occurrence in the outer Solar System and on comets. The maximum absorption coefficient in the generally broad 3-μm water band occurs near 3.1 μm (see, for example, ref. 6), which compares well with the spectrum of 24 Themis. However, the absorption coefficient for water ice near 3.1 μm is very large, so even what is normally considered a short path length produces a strong, very broad, saturated band, typical of that seen on icy satellites of the outer Solar System. Intimate ('salt-and-pepper') mixtures, even using 1-μm-sized grains in a Hapke–Mie hybrid model (see, for example, ref. 7), do not match the feature in the spectrum of 24 Themis.

One way to generate shorter path lengths through water ice, as indicated by the spectrum, is for the underlying grains to be coated in a thin film of ice. We modelled coated grains using the procedure outlined in ref. 8 (see Supplementary Information for details of our implementation). Using this model, we were able to reproduce the absorption band of 24 Themis very well with thin coatings of water ice over a variety of materials. The film thickness that best matches the shape of the 24 Themis spectrum is between 0.01 and 0.1 μm. A typical example is shown in Fig. 1 (applications to all of the four best-quality spectra are shown in Supplementary Fig. 3). We therefore conclude that the surface of 24 Themis contains very fine water frost, probably in the form of grain coatings.

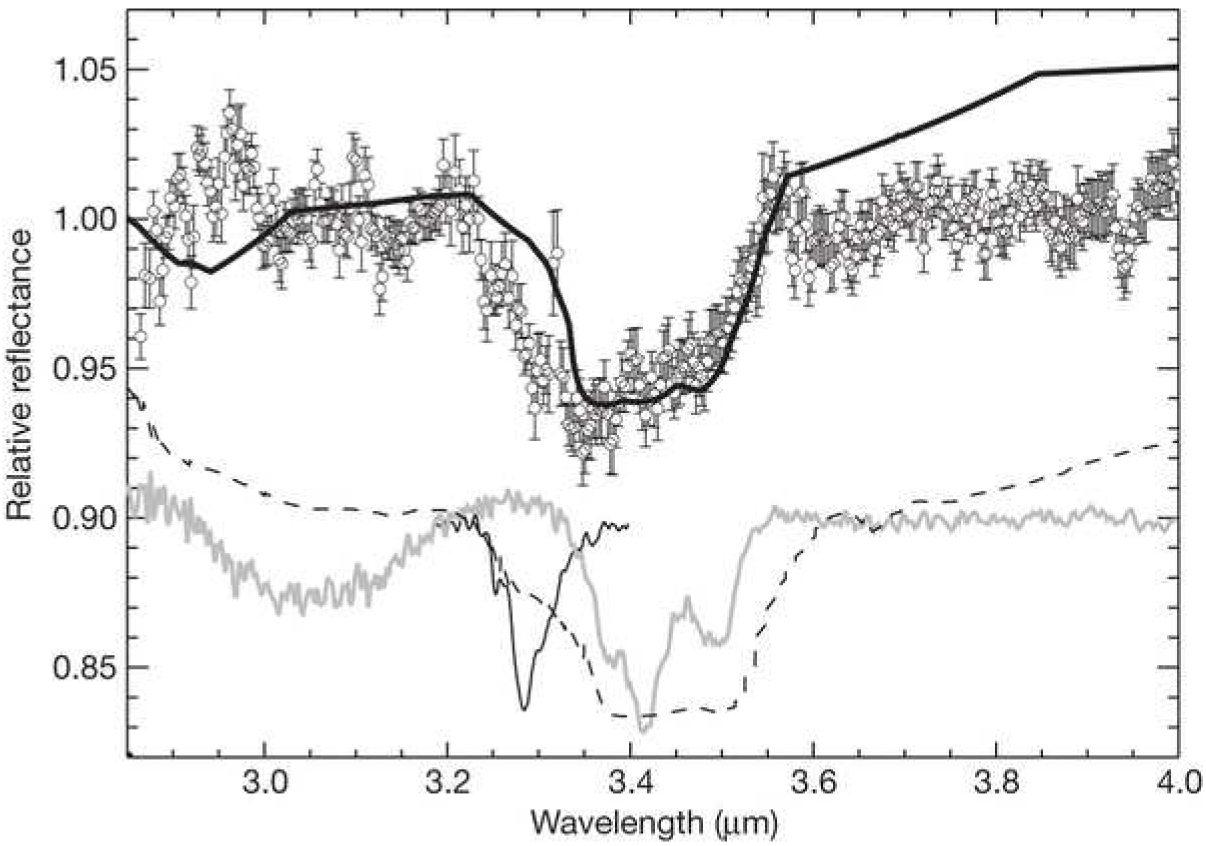
Figure 1: The reflectance spectra of 24 Themis are well fitted by a mixture of ice-coated pyroxene grains and amorphous carbon.



The spectrum of 24 Themis from 2008 (filled symbols) is plotted (binned ×6) along with an example spectral model that includes a thin coating of water ice on surface grains (grey line). The 24 Themis data are binned to lower spectral resolution and plotted as geometric albedo. The model is an intimate mixture containing 29% pyroxene coated with a 0.045-μm-thick layer of water ice and 71% amorphous carbon[6, 14]. All grains have a diameter of 30 μm. Error bars, 1 sample s.d.

After modelling of the ice feature, which dominates the spectrum, the residuals show evidence of additional spectral structure (Fig. 2). The features seen after removal of the model ice spectrum can be attributed to the presence of various organic materials[9, 10, 11]. The position and shape of the feature in the spectrum of 24 Themis suggests that it is caused by C–H stretching in $–CH_2$ and $–CH_3$ functional groups, although the absorption near 3.3 μm may indicate the presence of aromatic groups as well. The reflectance spectrum of 24 Themis in the 2–4-μm region can be fully explained by a mixture of spectrally neutral material, water ice frost and organic material.

Figure 2: Organic material is present on the surface of 24 Themis.



The spectrum of 24 Themis from 2008 has been divided by the model shown in Fig. 1 to identify residual absorptions (open symbols). A residual absorption band centred near 3.4 µm and with a width of ~0.2 µm is well matched by complex organic materials. The thick black line is ice tholin (the residual of an irradiated mixture of water ice and ethane; calculated from optical constants; ref. 9). Offset from the ice tholin and the spectrum/model data by 0.1 units, the dashed line is asphaltite[15], the heavy grey line is the carbonaceous meteorite Cold Bokkeveld (a slope from hydrated silicates has been removed; ref. 11) and the thin black line is an average of six polycyclic aromatic hydrocarbons (ref. 10). Absorption features in organic materials near 3.4 and 3.5 µm are typically $–CH_2$ and $–CH_3$ stretch bands, whereas those near 3.3 µm in the polycyclic aromatic hydrocarbons are aromatic stretch bands. Error bars, 1 sample s.d.

Given that ice will rapidly sublime at main-belt asteroid surface temperatures (~210 K for the subsolar point of 24 Themis), its presence in surface spectra may be suggestive of recent or continuing activity on 24 Themis. The presence of ice in the regolith of 24 Themis might be most easily explained as a result of a slow, steady outgassing from the asteroid's interior, with some amount of vapour recondensing as frost on regolith grains. Detailed modelling of the depth to an ice layer and of the rate of ice loss and condensation on 24 Themis is beyond the scope of this Letter, although work on the MBCs shows that on objects such as 24 Themis, ice can survive at depths as shallow as a few metres at latitudes poleward of 30° for all obliquities (and at all latitudes for moderate and high obliquities)[12].

For realistic values of thermal inertia, and the temperatures at the lowest latitudes of interest, we estimate an ice lifetime of thousands of years for the modelled coating thicknesses, with lifetimes in the millions of years at higher latitudes. An order-of-magnitude calculation, assuming carbonaceous-chondrite-like values for the original water fraction, a water loss rate for a temperature of 145 K and very liberal assumptions favouring water loss, finds enough water in the top 2 km alone of the surface of 24 Themis to last longer than the current age of the Solar System. Therefore, we do not find ice coatings inconsistent with the thermal properties of 24 Themis.

The outgassing picture is consistent with the observed cometary activity of the MBCs. Three of the known MBCs are members of the Themis dynamical family, and theoretical arguments have been used to conclude that their activity must be driven by ice sublimation, perhaps triggered by recent impacts. In this case, the discovery of ice on 24 Themis serves as confirmation that ice exists in objects of the Themis family and is a plausible driver of MBC activity. The differences observed in activity between the MBCs and 24 Themis may simply reflect a slow, steady-state outgassing and cold-trapping of ice on Themis, rather than sudden exposure and rapid outgassing on a few MBCs after an impact exposing subsurface ice. It also could be related to the much higher escape speeds on 24 Themis, which are greater than those on the largest MBCs by a factor of at least 20.

It is also of note that we do not see evidence of OH-bearing minerals, such as phyllosilicates, on 24 Themis. These minerals are common in the carbonaceous chondrites and among many similar asteroids such as 2 Pallas and 13 Egeria. Models of aqueous alteration in asteroids suggest that because the reactions are exothermic, they self-accelerate once begun, consuming all available ice and/or fully altering available silicates[13]. As a result, the lack of aqueous alteration products on the surface of 24 Themis is consistent with the idea that such alteration did not occur there or on other members of the Themis dynamical family. It also is consistent with the continued presence of ice, which would otherwise have been consumed by the alteration.

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Contributions

A.S.R. performed all of the telescopic observations and reduced all of the data, including the thermal flux removal. J.P.E. performed the spectral modelling of the ice and organics and performed spectral library searches. The authors contributed equally to interpretation and analysis.

Competing financial interests

The authors declare no competing financial interests.

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